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We have pursued a vigorous program of experimental and theoretical research on a novel method of frequency division based on an optical parametric oscillator (OPO). We have successfully demonstrated optical frequency division in a nearly degenerate KTP OPO that is highly efficient and tunable. The difference frequency of the two subharmonic outputs of the OPO was phase locked to a 12-GHz microwave source with a residual phase noise spectral density of 0.3 mrad/$\sqrt{\text{Hz}}$. More recently the use of a THz optical frequency comb permitted the OPO to be phase locked at a difference frequency of 665 GHz. We have studied a number of potential applications including optical frequency counting for frequency standards and multi-THz optical frequency comb generation for optical communications.

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# FINAL REPORT

Optical Frequency Division using an Optical Parametric Oscillator

U. S. Army Research Office
Grant DAAL03-90-G-0128

Covering the Period
May 1, 1990 - July 31, 1993



Submitted by


Ngai C. Wong
Principal Investigator


August 6, 1993


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# Contents

# 1 Statement of Work

A novel method of optical frequency division has been proposed based on optical parametric oscillation in a nonlinear crystal. The scheme converts with high efficiency an input pump into two intense, coherent subharmonic outputs whose frequencies are tunable and whose sum frequency equals the pump frequency. By locking the difference frequency of the outputs to a microwave frequency source, the output frequencies are precisely determined, and the optical parametric oscillator (OPO) functions as a frequency divider. OPO-dividers can be operated in series or in parallel to measure, compare, and synthesize frequencies from optical to microwave, with high precision and resolution. Potential applications of OPO-dividers include optical frequency standards, precision measurements, fiber-based and satellite optical communications. The main focus of this work has been to demonstrate a working optical frequency divider and apply it to the precise measurement and comparison of optical frequencies.

# 2 Research Summary

Under ARO Grant DAAL03-90-G-0128 "Optical Frequency Division using an Optical Parametric Oscillator," we have pursued a vigorous program of experimental and theoretical research on optical frequency division and its applications. In this final report on that grant we shall only summarize the principal results that we have obtained. Complete details can be found in the journal articles and meeting presentations that have been produced during the course of our research program.

## 2.1 Phase-locked Optical Parametric Oscillator

We have developed a cw optical parametric oscillator (OPO) that is highly stable and tunable over several THz [1, 2]. Continuous frequency tuning capability was enabled by fast electro-optic tuning and slow thermal tuning. Single-mode operation was obtained even in the free-running mode due to improved mechanical stability of our OPO cavity. We reported in [1, 2] the first demonstration of tunable optical frequency division based on optical parametric oscillation [3]. The signal-idler beat frequency of our potassium titanyl phosphate (KTP) OPO was phase locked to a 12-GHz microwave frequency source with excellent signal-to-noise ratio. The residual phase noise was measured to have a power spectral density of $\sim$0.3 mrad/$\sqrt{\text{Hz}}$. Because the beat frequency was controlled by a frequency synthesizer, the phase-locked outputs could be frequency tuned precisely.

More recently, we have achieved phase locking of our KTP OPO at a difference frequency of 665 GHz [4]. This was accomplished by generating a 2-THz optical frequency comb from the idler input and phase locking the beat between the signal and the 39th sideband of the comb. The optical frequency comb was obtained using a resonant electro-optic modulator driven with a 17-GHz modulation source. This

high-frequency capability makes possible precision difference-frequency measurements in the THz range. Also, the OPO can be used as a dual-frequency tunable optical source for the optical generation of terahertz radiation.

## 2.2 Optical Frequency Counting and Synthesis

In [5] we have proposed a new method of performing high-precision, high-accuracy optical frequency counting and synthesis fron the UV to the near-IR. The basic concept is to phase lock a parallel array of OPO frequency dividers to form an ultrawide-span optical frequency comb. By generating the subharmonic frequencies $(2/3)f_p$ and $(1/2)f_p$, where $f_p$ is the pump frequency, and measuring their frequency spacing with additional OPO's, the entire frequency comb can be calibrated relative to the cesium microwave frequency standard. As a result any optical frequency within this optical frequency comb can be measured using a single apparatus with accuracy limited only by the cesium clock. This is potentially useful for optical frequency standards, ultrahigh precision measurements, space-based optical communication networks such as global positioning system (GPS).

## 2.3 Other Applications

We explored in [6] the use of a smaller parallel array of OPO's to form an optical frequency comb with a span of 10 THz or more in the 1.55-$\mu$m optical communication window of silica-based optical fibers. It can be used in a dense coherent optical communication architecture in which a central node of a network distributes and maintains thousands of channel frequencies and their re-use. By locking one of the comb frequencies or the pump frequency to an atomic frequency reference, the entire frequency comb is calibrated and the high accuracy of the comb should make it

possible to create a densely packed network, thus increasing its capacity.

We have also investigated the use of a dual-cavity OPO for the detection of gravity waves [7]. By using an OPO in which the signal and idler beams are internally separated to traverse orthogonal optical paths and measuring the phase of their beat frequency, we have shown that it has the same sensitivity of the usual laser-based gravity wave antenna. The nonresonant nature of parametric oscillation in a nonlinear crystal implies that the system can have very low losses and a very high cavity finesse can be maintained. Heterodyne measurements reduce the effects of certain technical noise sources that have a high noise content at low frequencies. Also, the sensitivity of the OPO phase noise on the pump laser phase noise is found to be much reduced and therefore the pump laser frequency stability requirement is less severe. A less ambitious application for a dual-cavity OPO is that of a high sensitivity strain gauge for measuring differential length variations.

# References

[1] D. Lee and N. C. Wong, "Tunable optical frequency division using a phase-locked optical parametric oscillator," Opt. Lett. **17**, 13-15 (1992).

[2] D. Lee and N. C. Wong, "Stabilization and tuning of a doubly resonant optical parametric oscillator," to appear in J. Opt. Soc. Am. B, September (1993).

[3] N. C. Wong, "Optical frequency division using an optical parametric oscillator," Opt. Lett. **15**, 1129-1131 (1990).

[4] L. R. Brothers, D. Lee, and N. C. Wong, "Terahertz optical frequency comb generation using a resonant phase-velocity-matched electro-optic modulator," to be published.

[5] N. C. Wong, "Optical frequency counting from the UV to the near IR," Opt. Lett. **17**, 1155-1157 (1992).

[6] N. C. Wong, "Proposal for a 10-THz precision optical frequency comb generator," IEEE Photon. Technol. Lett. **4**, 1166-1168 (1992).

[7] N. C. Wong, "Gravity-wave detection via an optical parametric oscillator," Phys. Rev. A **45**, 3176-3183 (1992).

# 3 Personnel

Research under Contract DAAL03-90-G-0128 was carried out by:

Dr. Ngai C. Wong, Principal Investigator

Dicky Lee, Graduate Student

# 4 List of Publications

The following journal articles report research performed under Grant DAAL03-90-G-0128:

1. D. Lee and N. C. Wong, "Tunable optical frequency division using a phase-locked optical parametric oscillator," Opt. Lett. **17**, 13-15 (1992).

2. N. C. Wong, "Gravity-wave detection via an optical parametric oscillator," Phys. Rev. A **45**, 3176-3183 (1992).

3. N. C. Wong, "Optical frequency counting from the UV to the near IR," Opt. Lett. **17**, 1155-1157 (1992).

4. N. C. Wong, "Proposal for a 10-THz precision optical frequency comb generator," IEEE Photon. Technol. Lett. **4**, 1166-1168 (1992).

5. D. Lee and N. C. Wong, "Stabilization and tuning of a doubly resonant optical parametric oscillator," to appear in J. Opt. Soc. Am. B, September (1993).

6. L. R. Brothers, D. Lee, and N. C. Wong, "Terahertz optical frequency comb generation using a resonant phase-velocity-matched electro-optic modulator," to be published.

# 5 List of Meeting Presentations

The following meeting presentations reported research performed under Grant DAAL03-90-G-0128:

1. N. C. Wong, "Optical Frequency Measurement and Synthesis using Optical Parametric Oscillators," *Technical Digest, 1990 Annual Meeting* (Opt. Soc. Am., Washington, D.C., 1990).

2. N. C. Wong, and D. Lee, "Experimental Demonstration of a Tunable Optical Frequency Divider," *1991 Spring Meeting*, (American Physical Society, Spring Meeting, Washington, D.C., 1991).

3. N. C. Wong and D. Lee, "A Tunable Optical Parametric Oscillator for Precision Measurements," *Technical Digest, 1991 Annual Meeting* (Opt. Soc. Am., Washington, D.C., 1991).

4. N. C. Wong, "Gravitational Wave Detection via an Optical Parametric Oscillator." *Technical Digest, 1991 Annual Meeting* (Opt. Soc. Am., Washington, D.C., 1991).

5. N. C. Wong, "Precise Optical Frequency Comb Generation based on Optical Parametric Oscillators." *Technical Digest, 1991 Annual Meeting* (Opt. Soc. Am., Washington, D.C., 1991).

6. N. C. Wong and D. Lee "Optical Parametric Division," *Proceedings of the 1992 IEEE Frequency Control Symposium,* Hershey, Pennsylvania, May 1992.

7. N. C. Wong, D. Lee, and L. R. Brothers, "Tunable Optical Frequency Division." *IQEC '92 Technical Digest* (Opt. Soc. Am., Washington, D.C., 1992).

8. N. C. Wong and D. Lee,"Optical Frequency Division using a Parametric Oscillator," *Technical Digest, 1992 Annual Meeting* (Opt. Soc. Am., Washington, D.C., 1992).

9. D. Lee and N. C. Wong "High-Performance Optical Parametric Oscillator," *Proceedings of the SPIE Frequency Stabilized Lasers and Their Applications*, Boston, Massachusetts, November 1992.

# 6 Patents and Patent Applications Pending

1. Ngai C. Wong, "Optical Parametric Oscillator Wideband Frequency Comb Generator," U.S. Patent No. 5,177,633, Jan 5, 1993.

2. Ngai C. Wong, "Optical Frequency Counter/Synthesizer Apparatus," filed, U.S. Patent and Trademark Office, April 1992.